RI 9531

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REPORT OF INVESTIGATIONS/1995

Rock Mechanics Study of Shaft Stability and Pillar Mining, Homestake Mine, Lead, SD

(In Three Parts)

1. Premining Geomechanical Modeling Using UTAH2

By W. G. Pariseau, J. C. Johnson, M. M. McDonald, and M. E. Poad

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

cm	centimeter	km	kilometer
GPa	gigapascal	m	meter
kg	kilogram	MPa	megapascal

U.S. Customary Units

ft	foot	psi	pound per square inch
in	inch	tr oz	troy ounce

ROCK MECHANICS STUDY OF SHAFT STABILITY AND PILLAR MINING, HOMESTAKE MINE, LEAD, SD

(In Three Parts)

1. Premining Geomechanical Modeling Using UTAH2

By W. G. Pariseau,[1] J. C. Johnson,[2] M. M. McDonald,[3] and M. E. Poad[4]

ABSTRACT

A U.S. Bureau of Mines case study of pillar recovery in high-grade ore near the Ross shaft at the Homestake Mine, Lead, SD, has demonstrated the usefulness of the finite-element method for the evaluation of shaft pillar mining plans and shaft stability. This report, one of three in a series describing the Ross shaft pillar case study, focuses on the premining stability analysis. The two-dimensional computer program UTAH2 was used in advance of pillar mining; results suggested that the shaft would remain stable.

Subsequent reports describe parts 2 and 3 of the study. In part 2, borehole extensometers and other instruments were installed to provide data for model verification and shaft monitoring. Results of the recalibrated two-dimensional model confirmed the premining stability evaluation. However, after mining began, great concern developed because of the appearance of cracks and other signs of ground movement over considerable distances from the area of active pillar mining. In part 3, an intense three-dimensional modeling effort using UTAH3 was initiated. The results again showed that the shaft would remain safe. Three-dimensional analyses of alternative pillar mining scenarios indicated that more of the shaft pillar ore reserve could be recovered than previously thought.

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INTRODUCTION

SHAFT PILLAR DESIGN

Shafts are the primary accessways to many underground mines. Damage from shaft accidents is expensive to repair; loss of access interrupts production and poses a threat to safety as well. Consequently, accurate design of shaft pillars for the eventual recovery of ore reserves from shaft pillars are important to the mining industry.

The general objective of shaft pillar design is to develop a system that will provide natural support sufficient to protect the shaft from extensive, damaging ground movement induced by mining outside the shaft pillar. The pillar should be large enough for this purpose, but should not be so large that the minable ore reserve is reduced. Concrete lining, lagging, or rock bolts and screening provide localized ground control and prevent small falls of rock loosened over time.

As economic conditions change through improved mining methods and more favorable commodity prices, and also during the later stages of mining, recovery of ore left in a shaft pillar may be considered. In this regard, pillar mining is usually more expensive than stope mining and must be done with great care because of the ever-present need to protect the shaft. Small pillars may be left within the larger shaft pillar during pillar mining.

The dimensions of the pillar, its location with respect to the shaft, and the extraction sequence are significant rock mechanics considerations. Important input data include local geology, extent of previous stoping and filling near a pillar, the present stress state, the properties of the surrounding rock mass, and the extraction sequence. The finite-element method is the preferred analysis technique when several rock types are present. Analysis output includes displacements caused by mining, safety factors, and strains and stresses in the area of interest.

The present state of technology requires two stages of analysis before a design can be applied. The first stage consists of comparing calculated output with mine measurements and observations of inelastic effects. Objectives of such comparisons are (1) to validate the numerical model and (2) to calibrate the model. Calibration determines the scale factors for extrapolating data on rock properties obtained during laboratory tests to the properties of an actual rock mass in a mine. Mine measurements are therefore essential. Early installation of stope instruments and feedback during the initial stages of pillar mining are highly desirable.

The second stage of analysis is an evaluation of alternative pillar designs and extraction sequences that minimize shaft movement over the period of pillar mining.

Important adjuncts to establishing reliable shaft pillar design methodologies are monitoring ground movement near the shaft and measuring loads and deformations of shaft sets. The objective of monitoring is to warn of the onset of movements that may threaten shaft stability. In this regard, monitoring allows for observation of long-term creep effects over a period of, for example, 50 years. Usually such long-term effects are not included in short-term design considerations. Shaft surveys may also be helpful.

ROSS SHAFT PILLAR STUDY

Because of the importance of shaft pillar design to the mining industry, research was undertaken at the Homestake Mine, Lead, SD, to investigate the extraction of valuable reserves within the Ross shaft pillar. The study was a cooperative effort and involved the U.S. Bureau of Mines, the Homestake Mining Co., and the University of Utah, Salt Lake City, UT. Table 1 shows the chronology of the main project phases.

Table 1.—Project chronology

Phase	Topic	Date
1 ...	Premining stability analysis	April 1987.
2 ...	Installation of instruments and validation of 2-dimensional model.	October 1987, March 1987.
3 ...	3-dimensional stability analysis	August 1990, August 1991.
4 ...	Installation of additional instruments and update of 3-dimensional model.	June 1994.

The results are described in the present series of three Reports of Investigations (RI's). Part 1 concerns a premining stability analysis done in early 1987 before pillar mining began. The analysis involved using the two-dimensional, finite-element computer code UTAH2. Many of the input data were obtained from an earlier study of vertical crater retreat mining between the 6950 and 7100 levels of the mine (Pariseau, 1986). The premining stability analysis indicated that the shaft would remain in elastic ground.

Pillar mining began below the 3650 level in late 1988. Shortly afterward, movement was observed on the 3200 level, where the shaft had been damaged in the early 1950's. In fact, it was this experience that led to definition of the existing shaft pillar. Additional pillars within the shaft pillar were then defined in response to the perceived threat of renewed ground movement.

Part 2 of the series describes the instruments installed near the first stopes below the 3650 level and in the shaft itself. Data from the stope instruments on the 3650 level were used to recalibrate the two-dimensional, finite-element model in early 1989. Mine observations near stope walls and the new model calibration studies indicated that the rock mass in the vicinity of the shaft pillar was more deformable and not as strong as assumed in the premining analysis. However, the rock mass adjacent to the shaft remained in the elastic domain throughout the application of a variety of updated, two-dimensional simulations of shaft pillar mining, thus confirming the original analysis.

Ground movement remote from the site where the pillar was first mined remained unexplained by model analyses and unpublished consultant reports. In this regard, two hypotheses evolved: (1) An unknown geologic feature, such as a fault, was present that transmitted or amplified effects remote from mining or (2) the geometry of the problem, especially that associated with old stopes on either side of the shaft pillar, was not modeled with sufficient accuracy in the two-dimensional simulations.

Part 3 describes the development of a three-dimensional model. The finite-element code UTAH3 was used in this analysis. Effects that were unexplained in the two-dimensional model, such as the puzzling load transfer mechanism, appeared to be a natural outcome in the three-dimensional simulations. The three-dimensional results once again confirmed the earlier work in the sense that the Ross shaft remained in elastic ground during computer-simulated mining of the shaft pillar ore reserve. Subsequent design analyses of alternative extraction sequences indicated that some of the additional pillars planned within the main shaft pillar were not necessary. Since the start of actual shaft pillar mining, thousands of tons of ore have been safely recovered; ground movement about the shaft continues to be within expectations.

This work is in support of the USBM mission to improve the safety and productivity of mining.

HOMESTAKE MINE

The Homestake Mine is located in the northern Black Hills of South Dakota (figure 1). Figure 2 shows the general layout of the mine, which is the oldest and deepest in North America. Development extends to the 8000 level [corresponding to 2,440 m (8,000 ft) below the surface], with the Yates and Ross shafts providing access. About 8,400 kg (270,000 tr oz) of gold and 1,500 kg (50,000 tr oz) of silver are recovered from 1.5 million metric tons (1.7 million short tons) of ore milled per year. Most of the ore reserve in the Ross shaft pillar lies between the 3200 and 3800 levels on the west side of the shaft. Stoping methods are mainly mechanized cut-and-fill and vertical crater retreat (Haptonstall, 1986).

Figure 3 shows the geology of the district. The ore is localized in the steeply dipping folds of the metamorphosed Precambrian Homestake Formation, which strikes in a northerly direction and plunges to the south (Slaughter, 1968). Major fold troughs are known as "ledges" and are favorable ore loci. The gold is found as free gold and is commonly associated with arsenopyrite, pyrrhotite, chlorite, and quartz. The Poorman Formation lies stratigraphically below the Homestake and forms the footwall; the Ellison Formation is above and forms the hanging wall. However, folding has often overturned the hanging wall and footwall formations. Foliation is well developed in the Poorman and to a lesser extent in the Ellison, while the Homestake tends to be more massive and often contains quartz lenses. The foliation imparts directional mechanical properties to the rock mass that are often observed in differences between crosscuts and drifts.

APPROACH TO PROBLEM

The problem approach included some consideration of practical criteria for shaft stability, but consisted mainly of computer-simulated mining for shaft wall safety.

PRACTICAL SHAFT STABILITY CRITERION

A practical criterion for shaft safety is one that limits deformation of the rock surrounding the shaft to an amount that can be tolerated by hoist operations. Deformation is used here in a general sense to mean displacements and strains. Although precise tolerances were not determined, it was reasonable to assume that as long as deformation was within the elastic range, displacements and strains would be tolerable. Indeed, small strains and displacements ensure elastic stability. This criterion was intended only as a guide for avoiding the development of a major ground control problem in the vicinity of the shaft. The absence of yielding ground near the shaft was thus a favorable indication of stability.

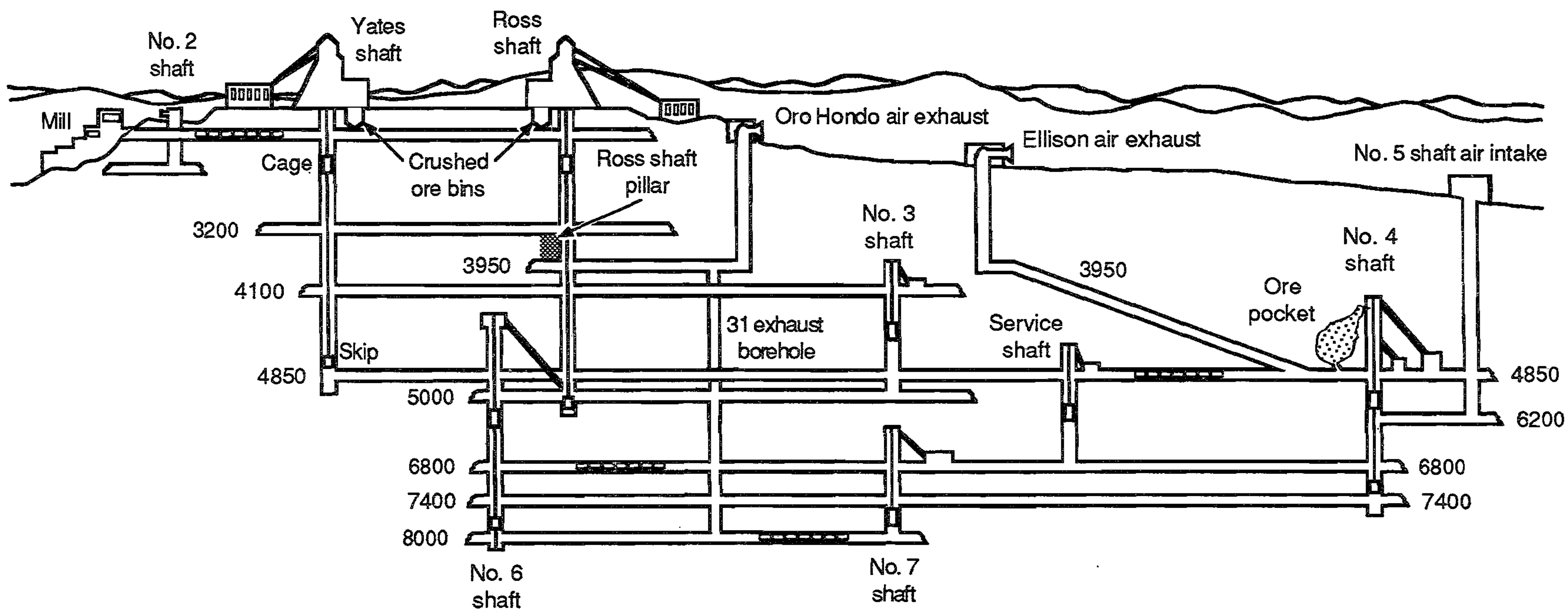
FINITE-ELEMENT PROGRAM

The two-dimensional, finite-element program UTAH2 (Pariseau, 1980; Pariseau and others, 1991) was used for all analyses during the premining phase of the project. This program simulates excavating and filling of initially stressed anisotropic rock masses. A generalized Hooke's law relates stresses and strains in the purely elastic

Figure 1

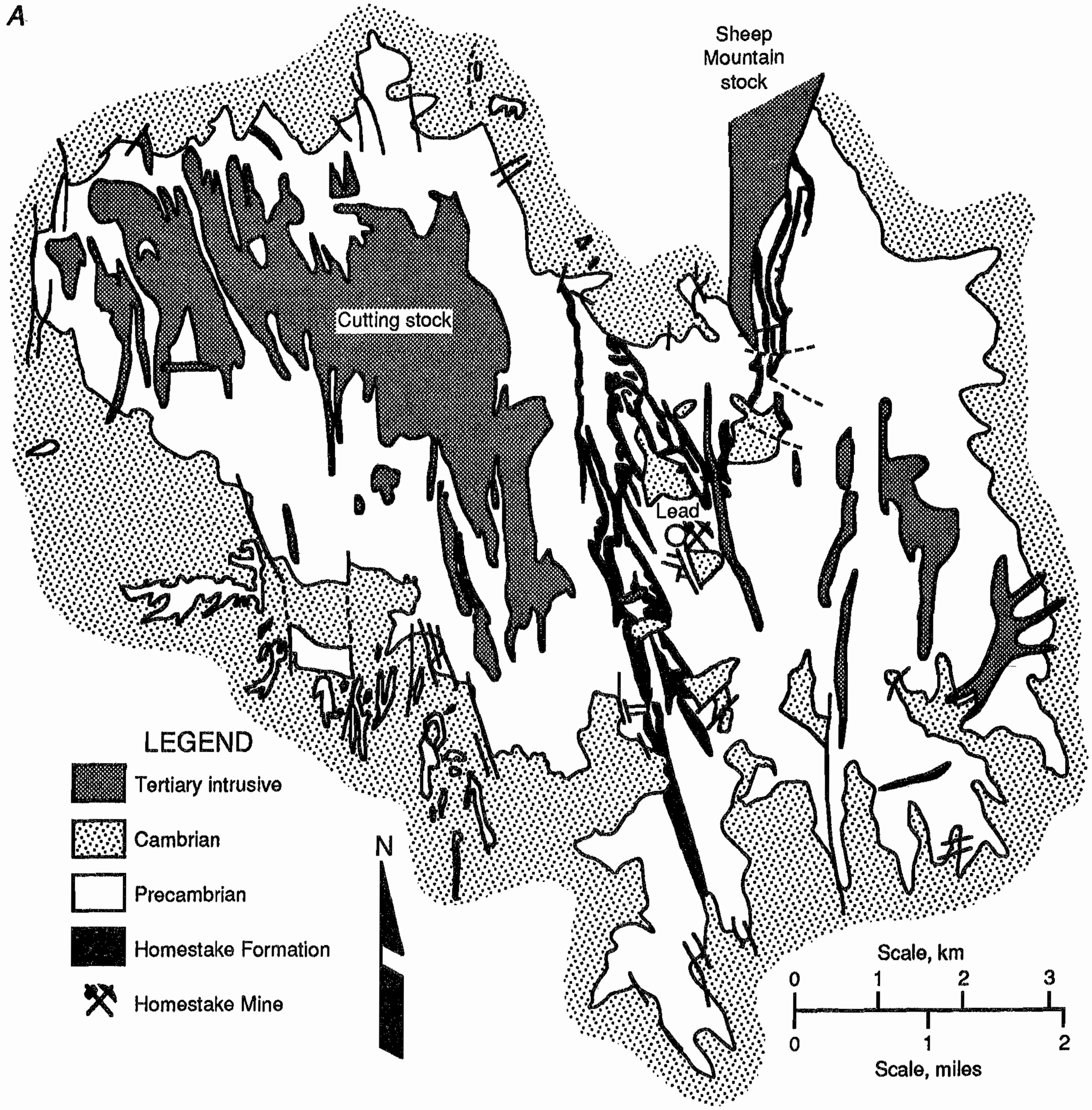
Location of Homestake Mine, USBM's Spokane Research Center, and University of Utah.

Figure 2



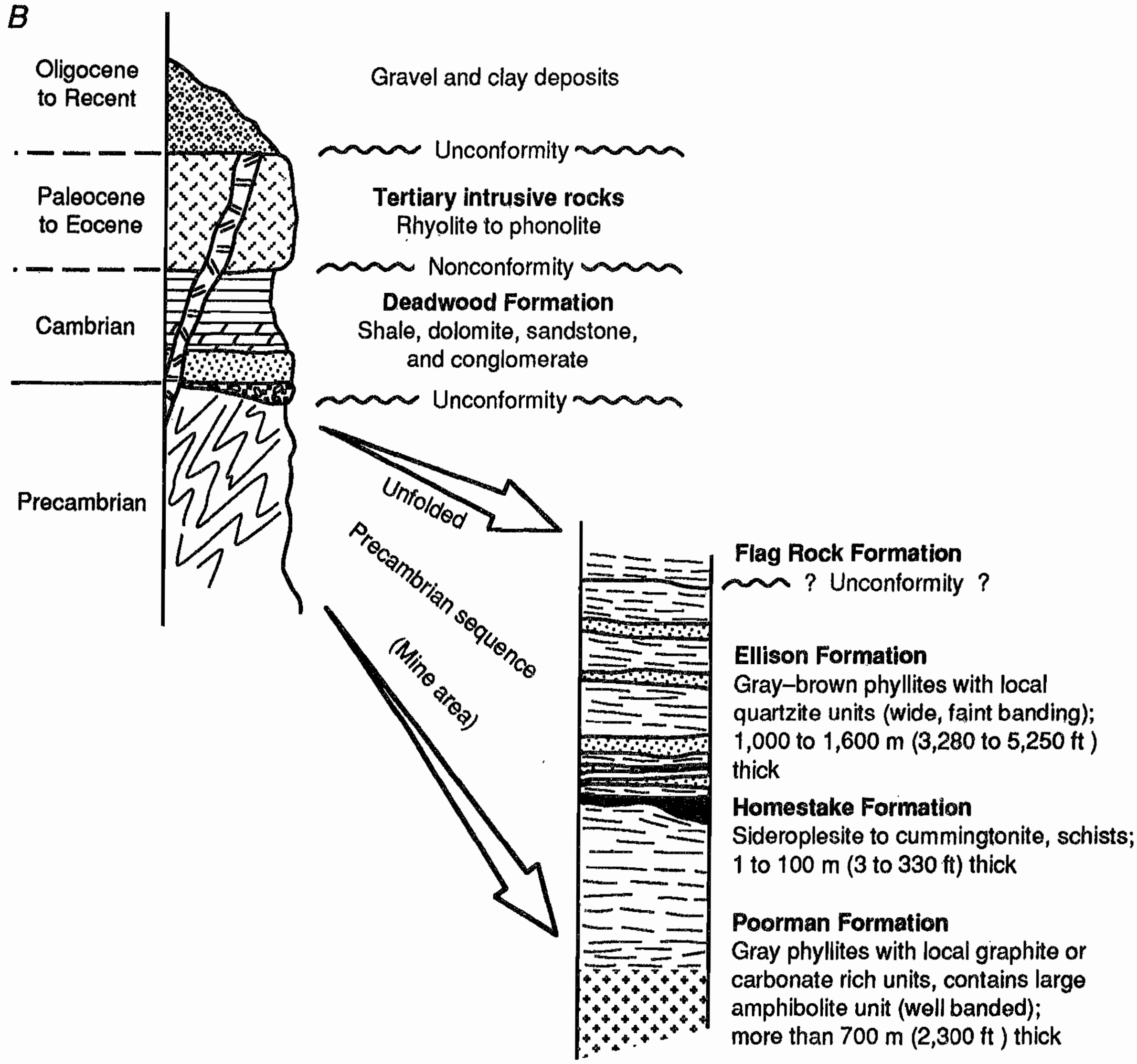
Schematic of Homestake Mine development.

Figure 3



Geology in vicinity of Homestake Mine. A, Areal geology. (After Slaughter, 1968)

Figure 3—Continued



Geology in vicinity of Homestake Mine. B, Stratigraphy. (After Slaughter, 1968) domain. A nonlinear, anisotropic yield condition appropriate for geologic media was used to limit the range of purely elastic deformation (Pariseau, 1972). Associated flow rules were applied when yielding occurred. Although the problem was actually three dimensional, a two-dimensional approach was selected for the initial phases of the study.

The first analysis involved a plan view of the 3500 level. The 3500 level was selected because it contained more of the ore-grade material in the shaft pillar than the other levels. Stopes were seen as parallel, shaft-like openings in plan view. Such a "shaft" view analysis was conservative in the sense that actual displacements would be less than computed displacements. Hence, if the ground about the Ross shaft appeared stable in plan view, the indication would be that mining in the shaft pillar did not pose a major threat to the shaft. A plan view also allowed assessment of shaft displacement in the horizontal plane of the 3500 level.

The second analysis involved a vertical cross section through the centerline of the shaft pillar. This section was perpendicular to formation strike. Stopes in cross section were seen as "tunnels" by the computer. The shaft could not be seen in cross section, although profiling the displacement of the trace of the shaft as a function of depth was possible.

ANALYSIS PROCEDURE

A successful analysis procedure used in an earlier study (Pariseau, 1986) was followed. In fact, the same initial stress state formulas, laboratory rock properties, and scale factors for extrapolating laboratory properties to field-scale properties were used. Additional stress measurements were subsequently made in the shaft pillar for the purpose of determining horizontal stress gradients (Johnson and others, 1993). Fill properties were estimated as those of a sandfill with some cement added.

The 3500-level geology, the old stope outlines, and the shaft pillar ore bodies were first traced from a mine map of the 3500 level and a section through the Ross shaft pillar. The stoping sequence was decided upon after reviewing historical information on mining in this area. However, the stoping sequence is not particularly important unless significant yielding develops.

After the contacts between the Homestake, the Ellison, and the Poorman Formations and the stope outlines were traced onto a large map (and section), the entire region was subdivided into elements. The coordinate data were then digitized and entered into computer files, as were the other data necessary for a finite-element simulation of shaft pillar mining. An important data file was the in situ or, synonymously, the premining, stress field. The in situ stress field was imposed on the model region before any mining was simulated by the computer.

The first simulated mining sequence involved the Ross shaft and 49 individual stopes and fills. In the first cut, elements occupied by the Ross shaft were excavated but not filled. However, fill was introduced sequentially as the old stopes were cut. Each new cut was followed by filling of the newly mined stopes before the next stopes were excavated. These operations were done automatically by the computer once the input run stream was established.

Output data consisted of the updated stress field and the strain and displacement changes that occurred during the program pass. Total strains and displacements, or equivalently, their histories, could be constructed from the sequence of output data files. The stresses were perhaps of greatest interest because they determined at any stage whether yielding occurred. They were continually updated during program execution. If the stress state in any element satisfied the yield condition, then the limit to a purely elastic deformation was reached. Subsequent deformation was elastic-plastic unless the element unloaded as a consequence of the redistribution of stress. The computer program, UTAH2, automatically handled the situation as it evolved.

INPUT DATA

The main input data were

1. Stope geometry and geology.
2. In situ stress state.
3. Rock and fill properties.
4. The mining sequence.

The nature of the input data was similar for the analyses of the plan view and the vertical section.

3500-LEVEL PLAN VIEW

Stope geometry and geology for the 3500-level plan view analysis are shown in figure 4. This figure also shows the subdivision of the region into finite elements. The number and size of the elements used are a practical tradeoff between desired detail and cost.

The in situ stress state refers to stresses in the area of the shaft pillar before any mining occurs (table 2). The prepillar mining stresses were obtained through simulating the historical mining sequence and were calculated from formulas described by Pariseau (1986). The ratio of in situ principal stresses (minor to major) seen in plan view is about one-half (0.520). This ratio characterizes the applied loads for the plan view study. The ratio for the vertical section (3500 level) is about 1 (0.899, to be exact).

Rock elastic moduli and strengths are listed in table 3. Laboratory values were scaled down to rock mass values according to scale factors determined in a previous rock mechanics study (Pariseau, 1986). The backfill properties given in table 4 are estimates based on laboratory tests of sandfill.

The plan view mining sequence is given in table 5. The cut sequence numbers include the stopes shown in figure 4, which also shows the plan view geology and location of the Ross shaft. Each cut in table 5 results in excavation of the listed stopes. Cuts 00 through 13 correspond to past mining, stopes 1 through 43, and the Ross shaft. Cuts 14 through 18 simulate mining in the shaft pillar, stopes 44 through 49. Stopes 1 through 43 are old stopes; stopes 44 through 49 were potential shaft pillar stopes. Simulated mining of the shaft pillar stopes began with the stope farthest from the shaft, stope 49, and proceeded toward the shaft. Stope 44 was the last stope mined in the analysis.

Table 2.—In situ stress model

Direction of stress component	Symbol	Formula[1]	Magnitude, MPa	Symbol	Formula[2]	Magnitude, psi
Vertical	σ_V	= 0.028 d	30	σ_V	= 1.25 d	4,375
East-west	σ_H	= 0.012 d + 14.3	27	σ_H	= 0.53 d + 2,078	3,933
North-south	σ_h	= 0.012 d + 0.8	14	σ_h	= 0.55 d + 121	2,046

[1]d = depth in meters.
[2]d = depth in feet.

NOTE.—Compresive stress is positive.

Table 3.—Laboratory test values for elastic and strength properties

Property and symbol	Homestake		Poorman		Ellison	
Young's modulus, GPa (psi):						
E_{aa} (∥-2)	88.3	(12.8×10^6)	93.1	(13.5×10^6)	89.6	(13.0×10^6)
E_{bb} (⊥)	64.1	(9.3×10^6)	49.6	(7.2×10^6)	63.4	(9.2×10^6)
E_{cc} (∥-1)	62.1	(9.0×10^6)	94.5	(13.7×10^6)	75.8	(11.0×10^6)
Shear modulus, GPa (psi):						
$G_{bc} = G_a$	33.1	(4.8×10^6)	26.2	(3.8×10^6)	31.7	(4.6×10^6)
$G_{ab} = G_c$	26.9	(3.9×10^6)	26.9	(3.9×10^6)	29.0	(4.2×10^6)
$G_{ca} = G_b$	29.7	(4.3×10^6)	38.6	(5.6×10^6)	75.8	(5.1×10^6)
Compressive strength, MPA (psi):						
C_{aa} (∥-2)	138.9	(20,150)	94.0	(13,630)	78.2	(11,340)
C_{bb} (⊥)	79.6	(11,550)	69.0	(10,000)	78.7	(11,410)
C_{cc} (∥-1)	91.5	(13,270)	84.6	(12,270)	56.2	(8,150)
Tensile strength, MPa (psi):						
T_{aa} (∥-2)	9.5	(1,378)	20.6	(2,900)	16.2	(2,350)
T_{bb} (⊥)	7.9	(1,140)	5.7	(820)	4.1	(590)
T_{cc} (∥-1)	13.2	(1,920)	13.2	(1,910)	11.4	(1,650)
Shear strength, MPa (psi):						
$R_{bc} = R_a$	14.1	(2,050)	10.3	(1,500)	7.9	(1,150)
$R_{ca} = R_b$	17.0	(2,470)	19.3	(2,800)	14.6	(2,120)
$R_{ac} = R_c$	14.5	(1,280)	8.8	(1,220)	8.6	(1,250)
Poisson's ratio:[1]						
ν_{ab} (ν_{ba})		0.14 (0.10)		0.23 (0.12)		0.20 (0.14)
ν_{bc} (ν_{cb})		0.18 (0.17)		0.15 (0.29)		0.17 (0.20)
ν_{ca} (ν_{ac})		0.19 (0.27)		0.22 (0.22)		0.15 (0.28)

[1]Order of subscripts is important:

a. Direction is down foliation dip, the parallel-two (∥-2) direction.

b. Direction is perpendicular to foliation (⊥).

c. Direction is parallel to foliation strike (∥-1).

Table 4.—Estimates of backfill properties,

(In megapascals pounds per square inch)

Property		
Young's modulus	1,655	(240,000)
Shear modulus	690	(100,000)
Compressive strength	2.8	(400)
Tensile strength	0.7	(100)
Shear strength[1]	0.8	(115)
Poisson's ratio		0.20

[1]Based on isotropy and a quadratic yield criterion.

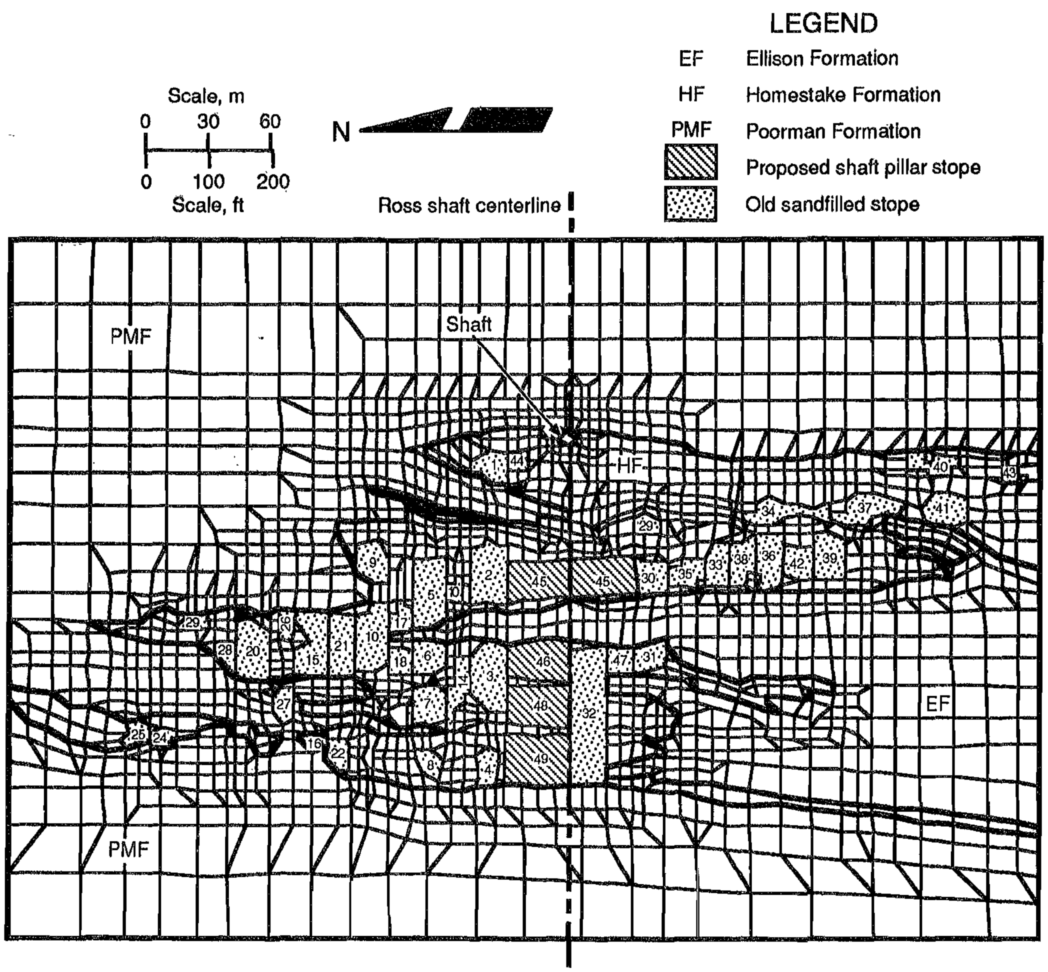
VERTICAL CENTER SECTION

Stope geometry and geology for the vertical section are shown in figure 5. Rock mass properties were the same as before. Old stopes were not present in the shaft pillar, so no simulation of historical mining was done. A pillar mining sequence had not been established at the time of the analysis, so the shaft pillar ore reserve was mined on the computer in a single program run.

Table 5.—Mining sequence for 3500-level plan view

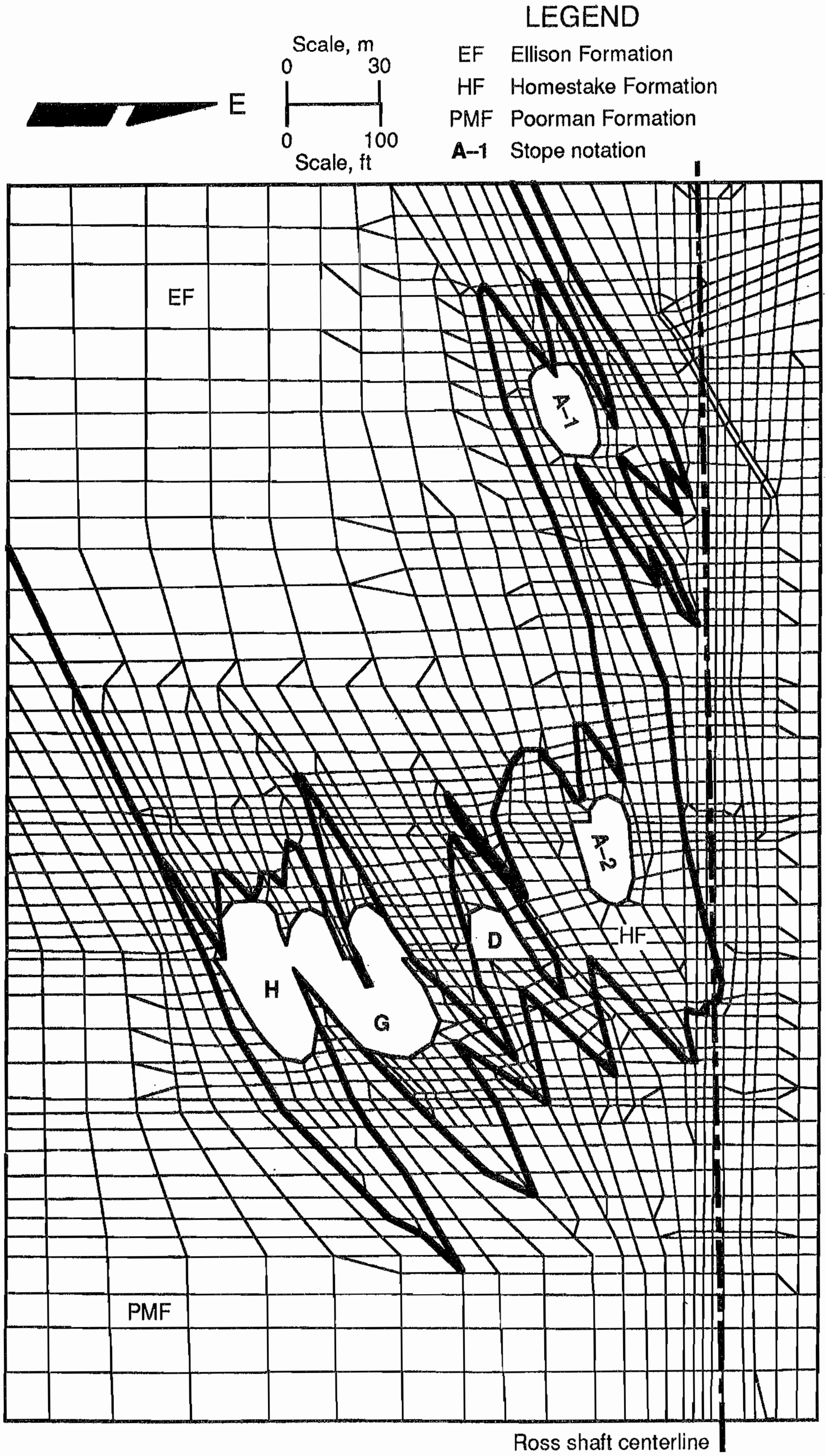
Cut sequence	*Cut-and-fill stopes mined*
Historic mining north of Ross shaft:	
00	Ross shaft cut
01	1-4
02	5-8
03	9-12
04	13-16
05	17-19
06	20-22
07	23-28
Historic mining south of Ross shaft:	
08	29-31
09	32
10	33-34
11	35-37
12	38-40
13	41-43
Mining in Ross shaft pillar:	
14	49
15	48
16	46-47
17	45
18	44

Figure 4



Finite-element plan view mesh. Numbers indicate stoping sequence.

Figure 5



Finite-element center plane section.

PREMINING STABILITY EVALUATION

The computer produced stress, strain, and displacement field changes as simulated mining proceeded. A strength criterion limited the range of a purely elastic response of any element. Yielding of an element followed loading beyond the elastic limit. A yielding element has a safety factor of 1; elements in the elastic range have higher safety factors. (The safety factor is the ratio of strength to stress.) Element safety factors were part of the computer output. These data were examined for the guidance they provided relative to the question of Ross shaft stability.

3500-LEVEL PLAN VIEW

Figure 6*A* shows the yielded elements in the 3500-level plan view after the old stopes had been mined and filled but before mining began in the shaft pillar. Figure 6*B* shows the yielded elements after the shaft pillar had been mined. Yielding was generally confined to areas adjacent to the old stopes. No yielding was observed near the shaft itself.

Figure 7 shows the principal stresses before and after pillar mining. The length of the line segments is proportional to the magnitude of the compression; tension, when present, is indicated by an arrowhead. Mining the stopes along strike reduced the y-direction (north-south) stress and brought its value closer to the original x-direction (east-west) stress. There was a slight trend toward equal (hydrostatic) principal stresses.

Figure 8*A* shows the displacements caused by mining the first shaft pillar stope (49); figure 8*B* shows the displacements caused by mining the large stope (45) near the shaft. The general pattern of incremental movement was toward the excavated stope, as expected.

Displacement histories at two of the shaft corners are shown in figure 9. In this figure, the pattern shows the shaft tended to move toward the active stoping areas, first to the left (negative x-direction) and down the page (negative y-direction), and then to the right, continuing down. Displacement increments in the x- and y-directions were less than 2.5 cm (1 in) until mining in the pillar began. The y-direction (east-west) displacements are the largest. Total pillar mining displacement was somewhat greater than 5 cm (2 in). The amount of displacement of the shaft corners was nearly equal, so that in this view, the shaft was only slightly distorted and tended to "float" with ground movement. In reality, displacements above and below the 3500 level would be less, and the shaft would deform in the vertical plane. This is a three-dimensional aspect of the problem that cannot be addressed in a two-dimensional view.

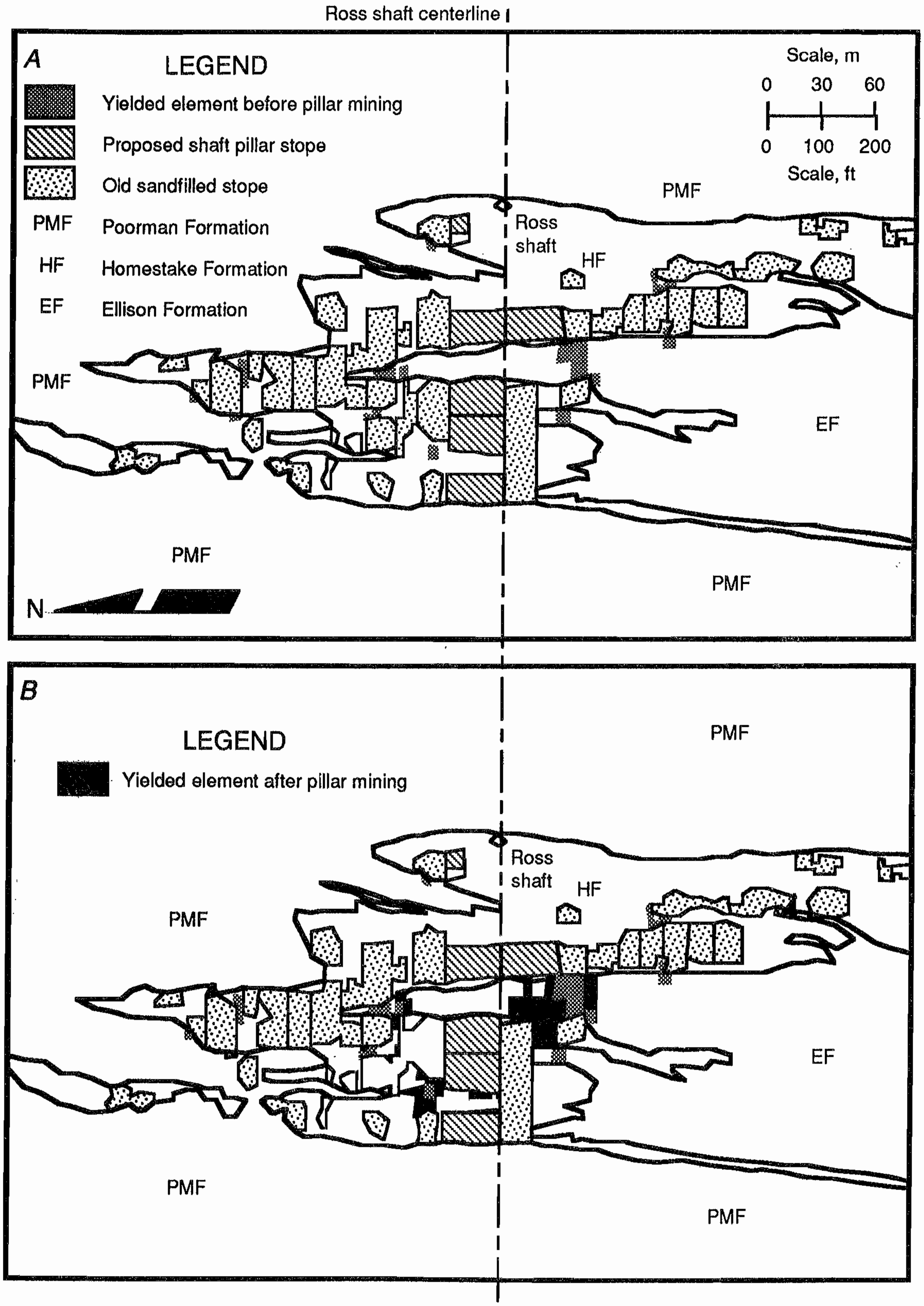
Figure 10 shows contours of the local safety factors after mining in the shaft pillar. Also shown in figure 10 are yielding elements before and after mining in the shaft pillar. The safety factor of a yielded element is 1. Interestingly, the safety factor in some areas near the shaft increases with pillar mining. This is a consequence of the initial stresses, rock properties, historical mining, and pillar mining geometry that combine to make the resulting stress state in the shaft area more stable than before. The safety factor increases because the principal shear stresses or principal (normal) stress differences are reduced. The contours in the vicinity of the shaft indicate stability.

VERTICAL CENTER SECTION

Figure 11 shows the geology and ore reserve geometry and yielded elements in the vertical section after the entire shaft pillar ore reserve was mined. The same in situ stress formulas and rock properties were used in the analysis of this section. However, the mining sequence was entirely different. In this analysis, the stopes in figure 11, which were in the shaft pillar, were mined in one cut. These stopes appeared as tunnels and, when mined, could be considered linked to the previously mined stopes that were offset into and out of the plane of the section.

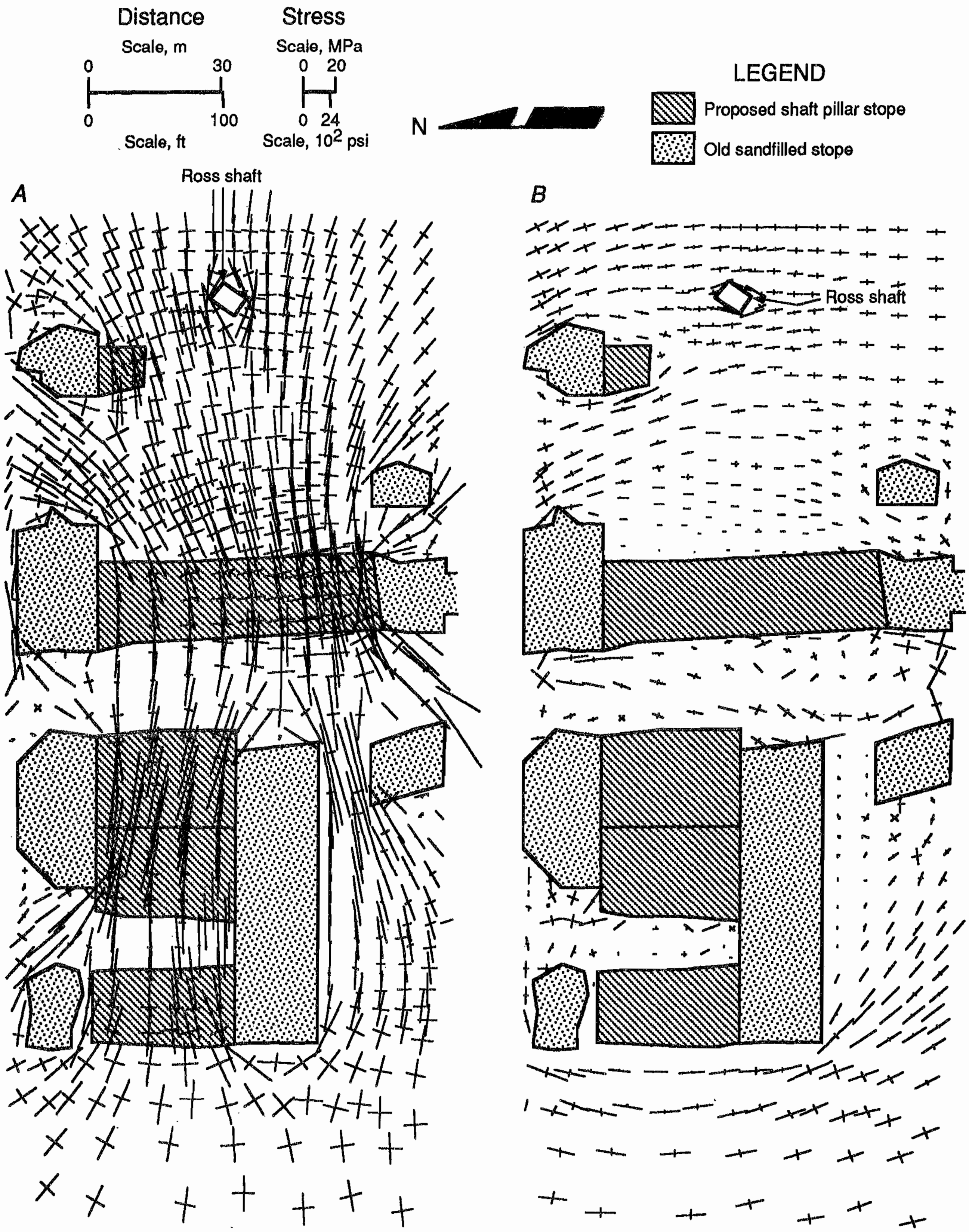
Figure 12 shows the safety factor contours after the stopes in the vertical section had been mined. Safety factors along the trace of the shaft were generally greater than 3.5, indicating stability. However, the shaft could not be represented in vertical section, so stress concentrations in the shaft wall were not taken into account in this analysis.

Figure 6



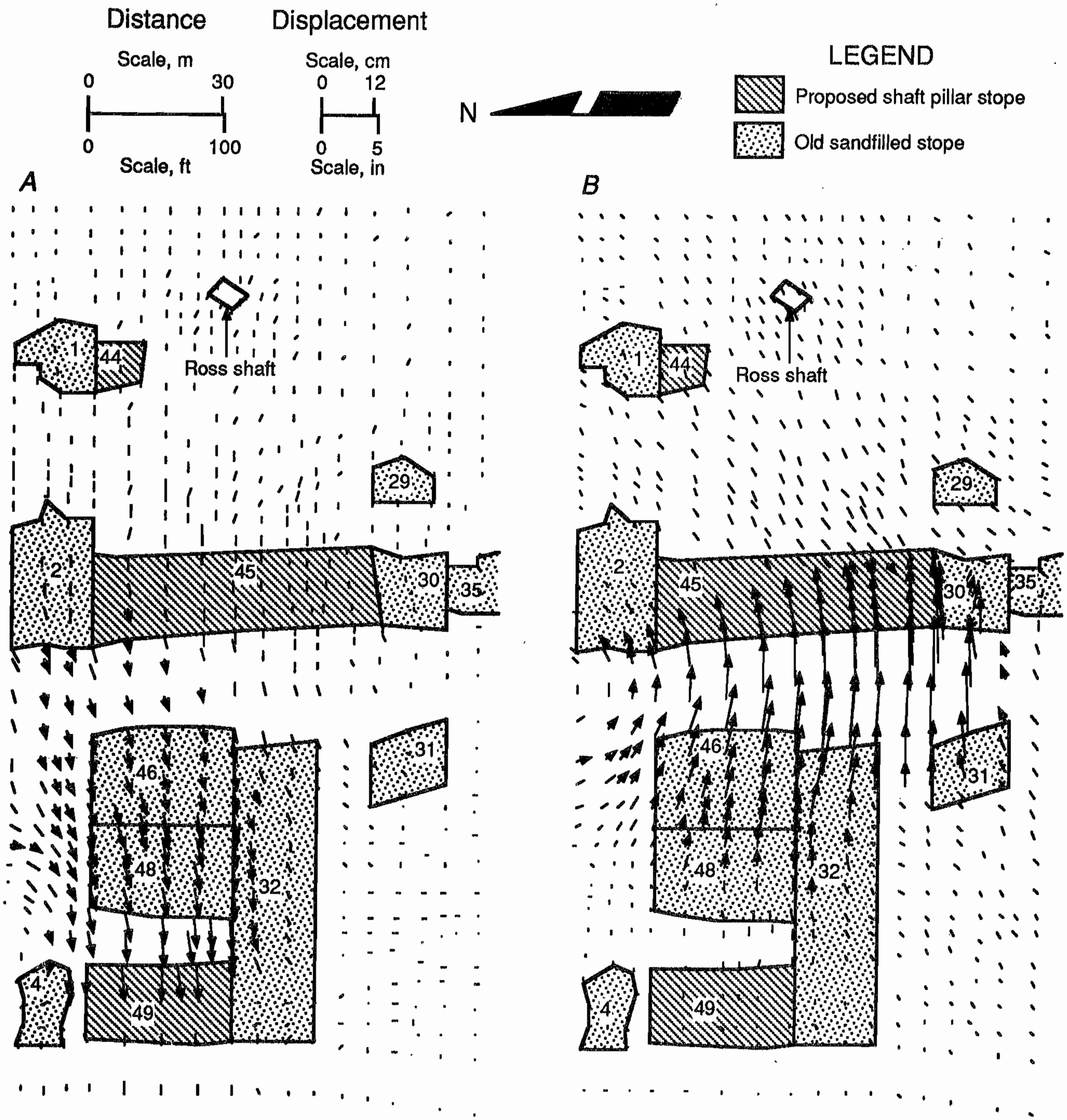
Yielding elements in 3500-level plan view. A, Before pillar mining; B, after pillar mining.

Figure 7



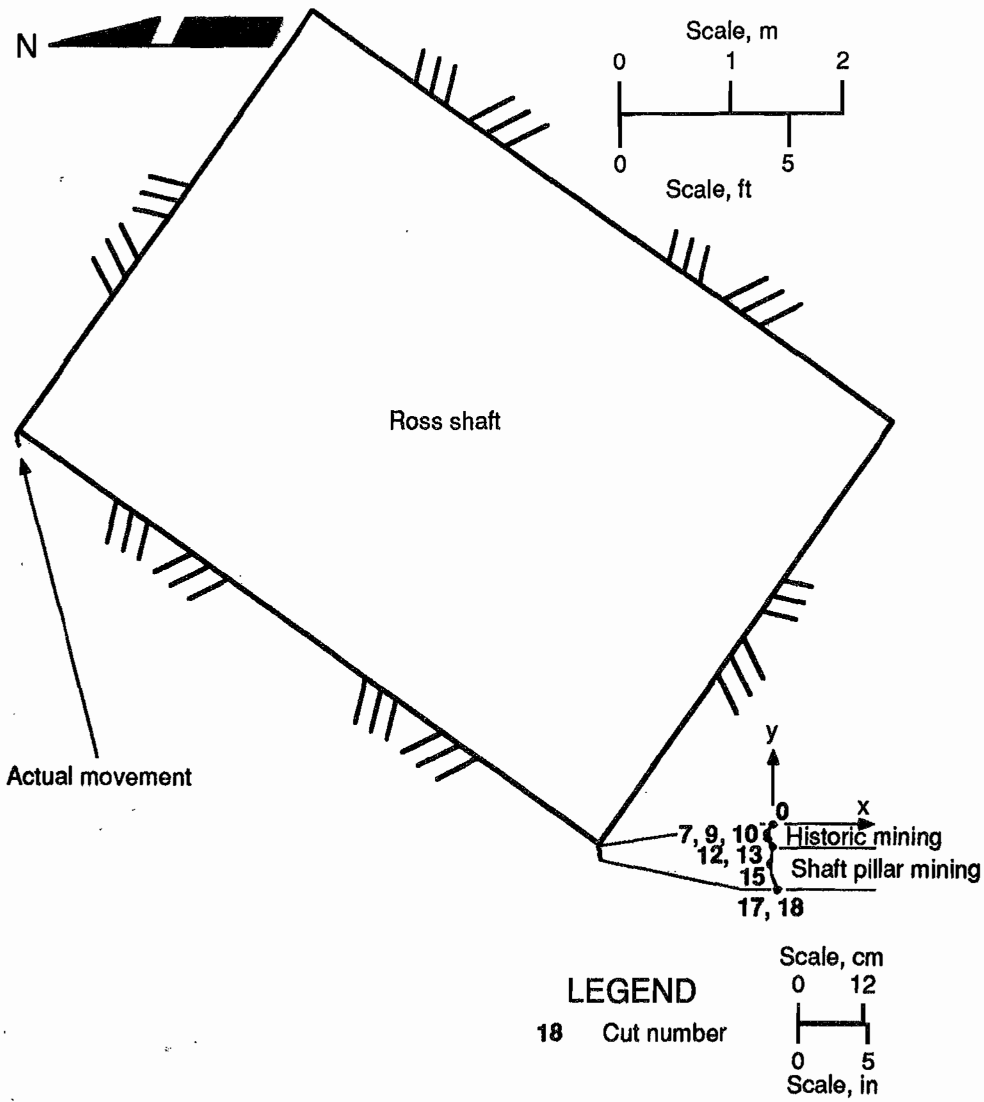
Principal stresses in 3500-level plan view. A, Before pillar mining; B, after pillar mining.

Figure 8



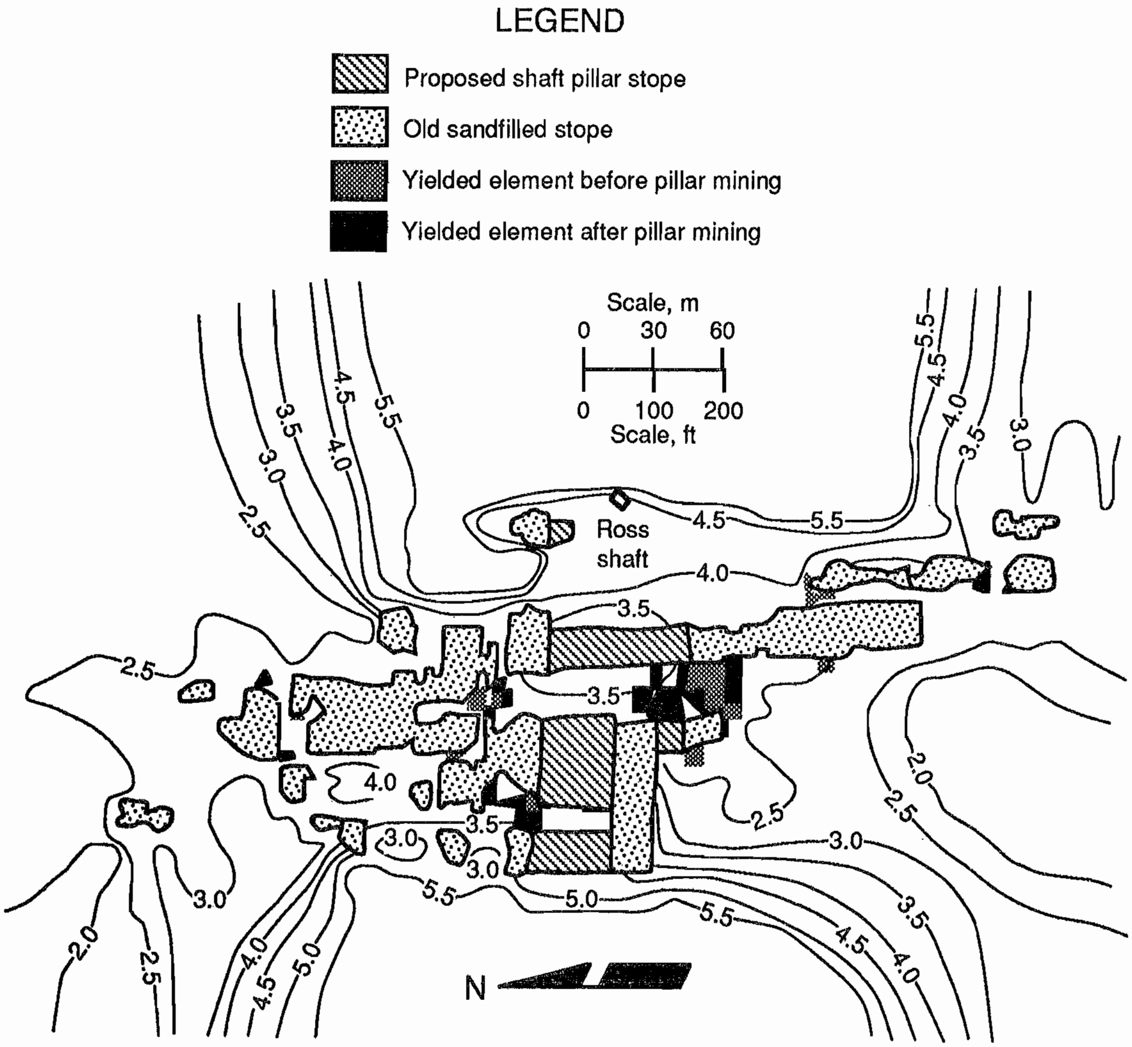
Displacement changes in 3500-level plan view. Numbers indicate mining sequence. A, After mining first shaft pillar stope 49; B, after mining shaft pillar stope 45 near the shaft.

Figure 9



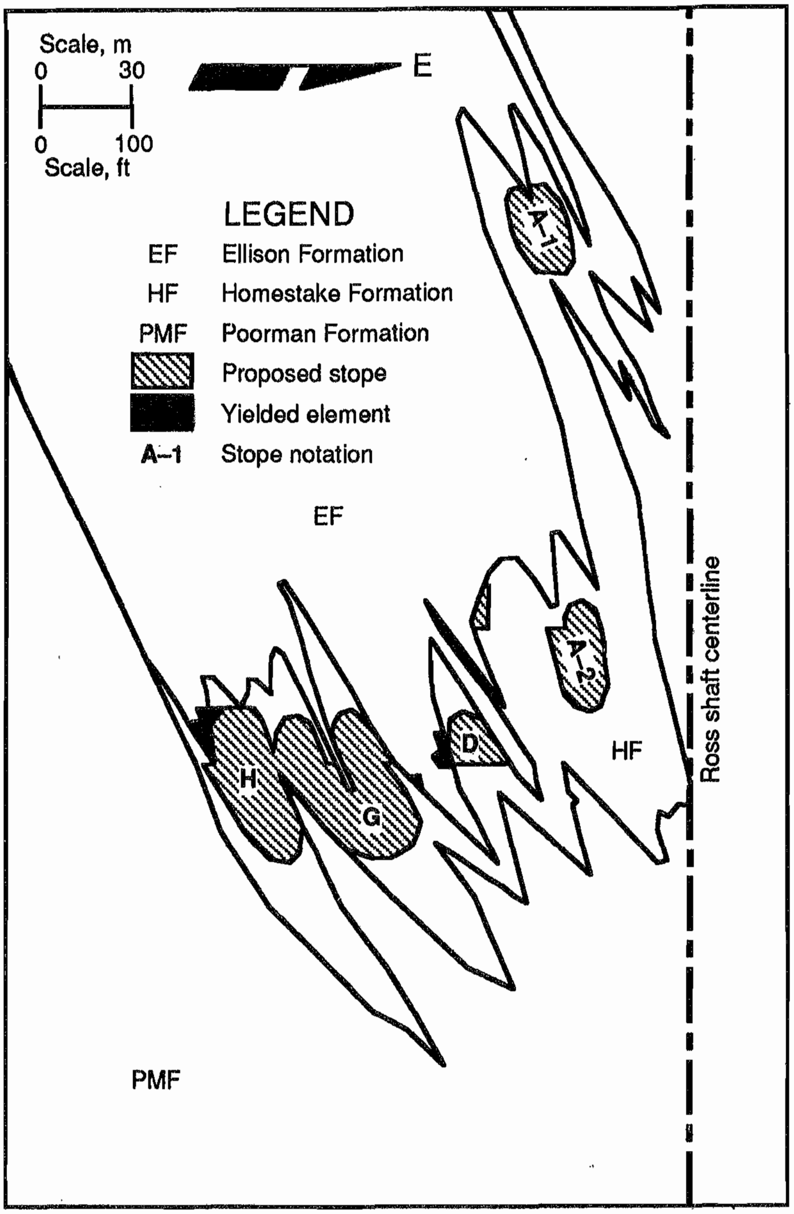
Computed shaft corner displacement histories in 3500-level plan view. Lower scale (in centimeters) indicates amount of shaft displacement; upper scale (in meters) indicates size of shaft.

Figure 10



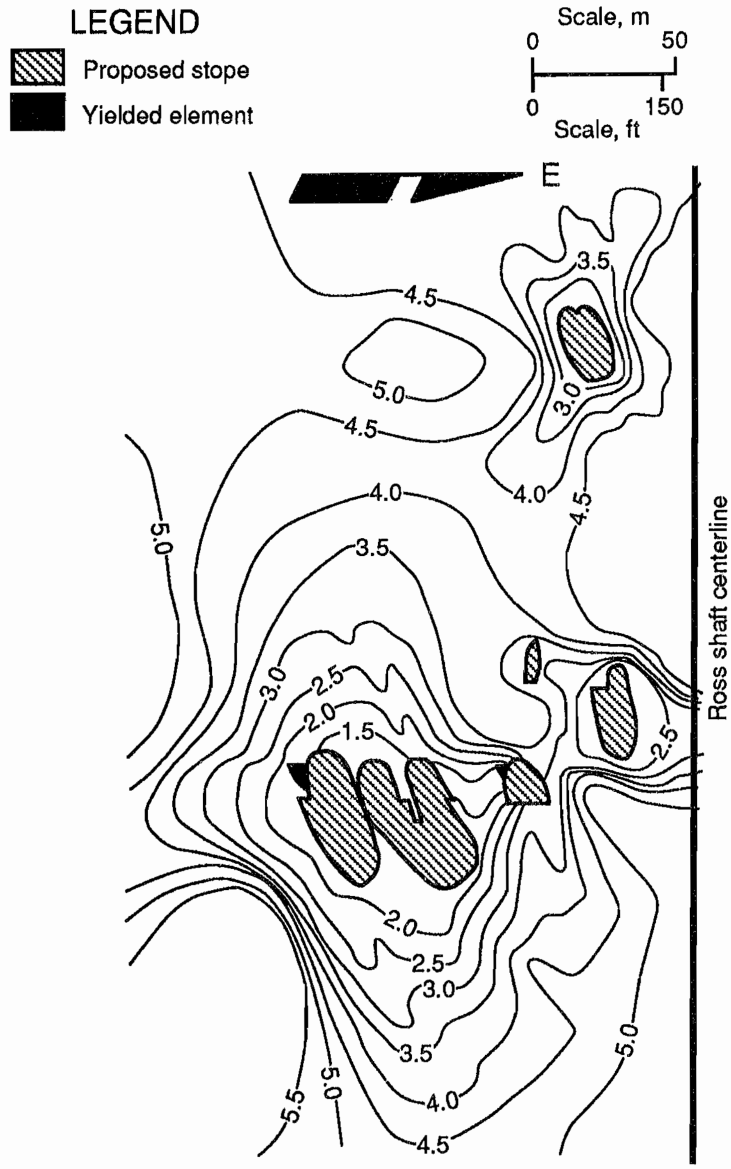
Safety factor contours in 3500-level plan view after pillar mining.

Figure 11



Yielding elements in vertical section after pillar mining.

Figure 12



Safety factor contours in vertical center section after pillar mining.

SUMMARY AND CONCLUSIONS

Advances in rock mechanics and mine design suggested that it might be possible to devise methods for recovering ore left in shaft pillars of hard-rock mines. A case study involving a shaft pillar in high-grade ore near the Ross shaft at the Homestake Mine demonstrated the usefulness of the new technology. A premining stability evaluation indicated that the shaft would remain in elastic ground if the ore reserve in the shaft pillar were mined. The approach involved using the two-dimensional, finite-element program UTAH2 for analyzing a plan view of the 3500 level of the shaft pillar and a vertical section through the center plane of the pillar. The meshes used in this initial study were relatively coarse and possibly too small to be entirely free of boundary effects. (These and related questions will be addressed in detail in part 2. Three-dimensional considerations will be addressed in part 3.) Computer-simulated mining of the ore reserve showed that the shaft would remain in elastic ground through shaft excavation, mining and filling of the old stopes, and mining in the shaft pillar. Yielding ground was confined to the neighborhood of the stopes and did not extend to the shaft. Large-scale ground movement and the potential for catastrophic failure were not indicated. Thus, results of the premining phase of the Ross shaft pillar study indicated that proposed pillar mining did not pose a threat to shaft stability.

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